LA-UR-19-30005

Title: Dark Matter Searches with HAWC

Author(s): Lundeen, Joseph Andrew

Intended for: International Cosmic Ray Conference, 2019-07-24 (Madison, Wisconsin, United States)

Issued: 2019-10-02

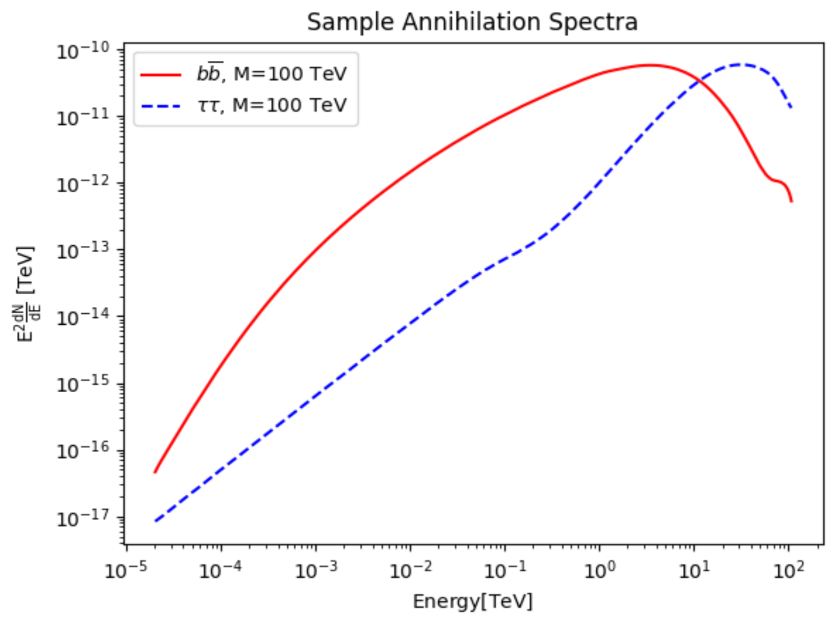
Dark Matter Searches with HAWC

Joe Lundeen for the HAWC Collaboration

July, 2019

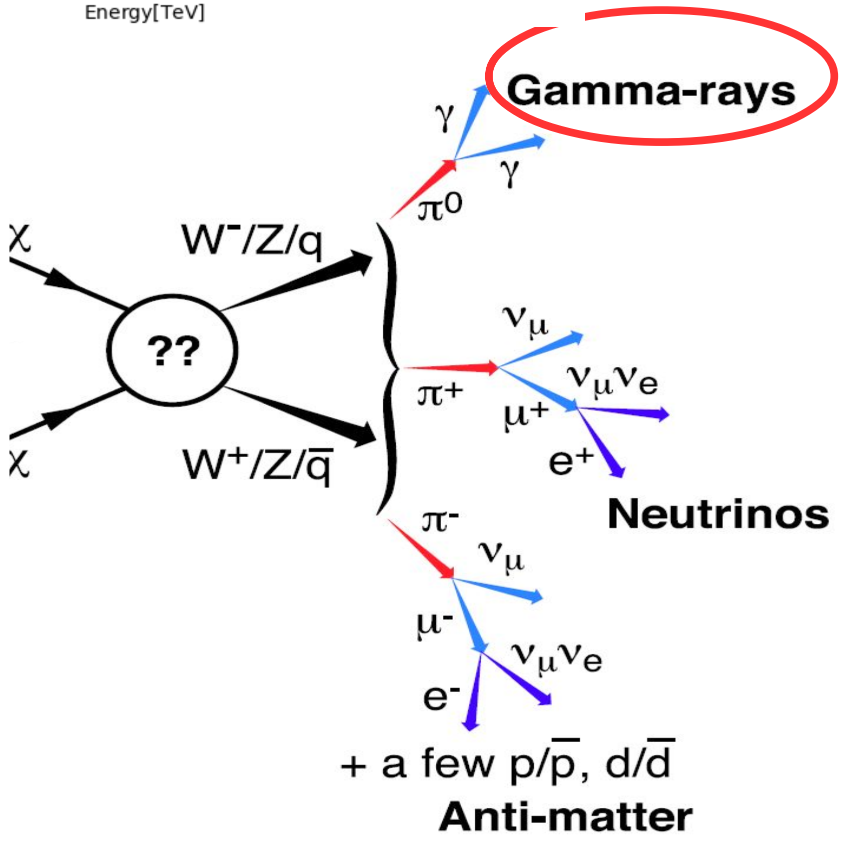
Continuous Spectra

- WIMP dark matter can annihilate or decay to standard model particles
  - Interaction products then produce photons
- Energy spectrum characterized by hard cutoff at DM mass
- Search for gamma-ray excesses with characteristic shape originating from known DM halos
- Can constrain velocity-weighted cross section or decay lifetime
- Emphasis on multi-TeV mass dark matter



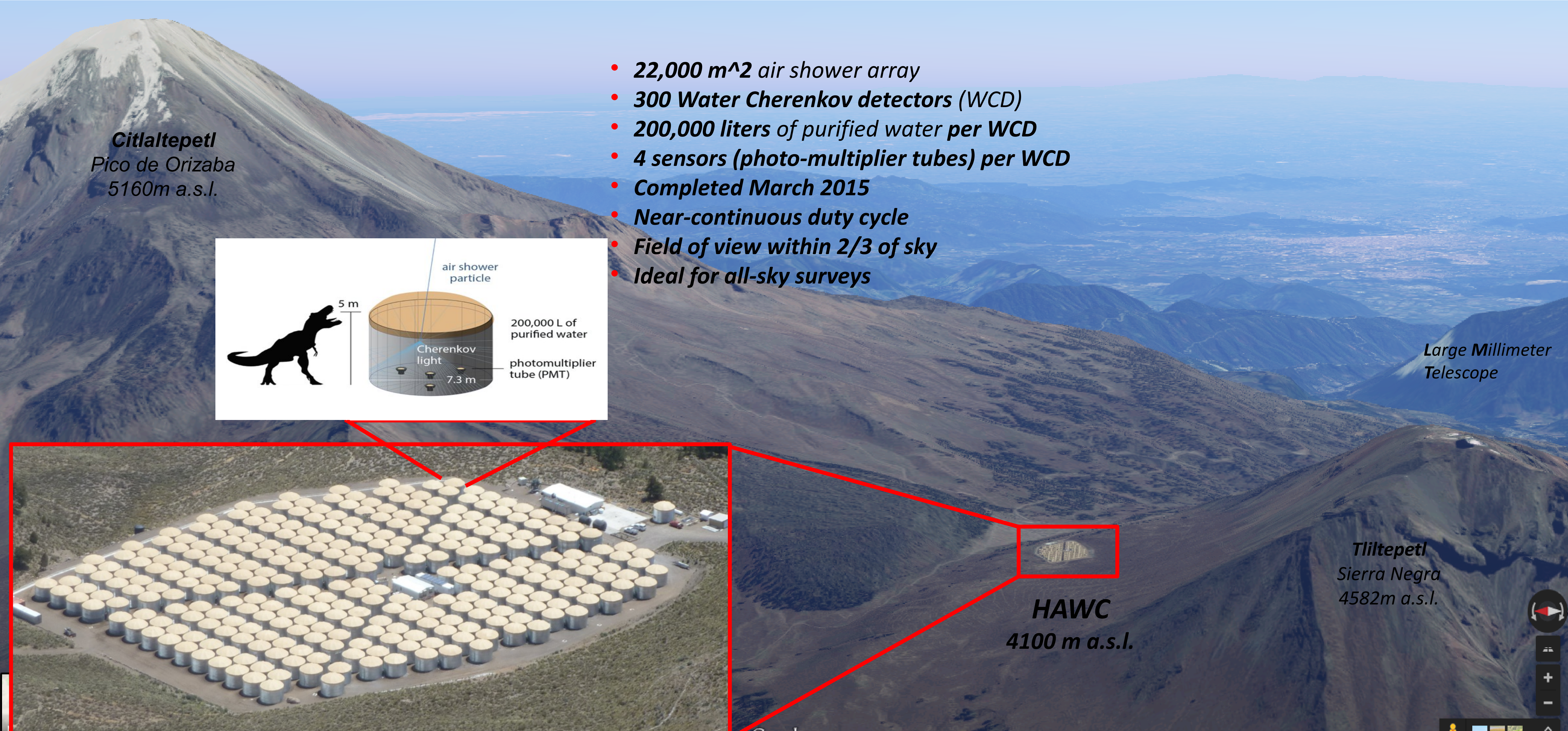
$$\frac{d\Phi}{dE}_{annihilation} = \frac{J}{8\pi}\frac{\langle\sigma v\rangle}{M^2}\frac{dN(M, channel)}{dE} \qquad \frac{d\Phi}{dE}_{decay} = \frac{D}{4\pi}\frac{1}{\tau M}\frac{dN(M, channel)}{dE}$$

$$J = \int\int \rho_{dm}^2(l,\Omega)dld\Omega \qquad D = \int\int \rho_{dm}(l,\Omega)dld\Omega$$



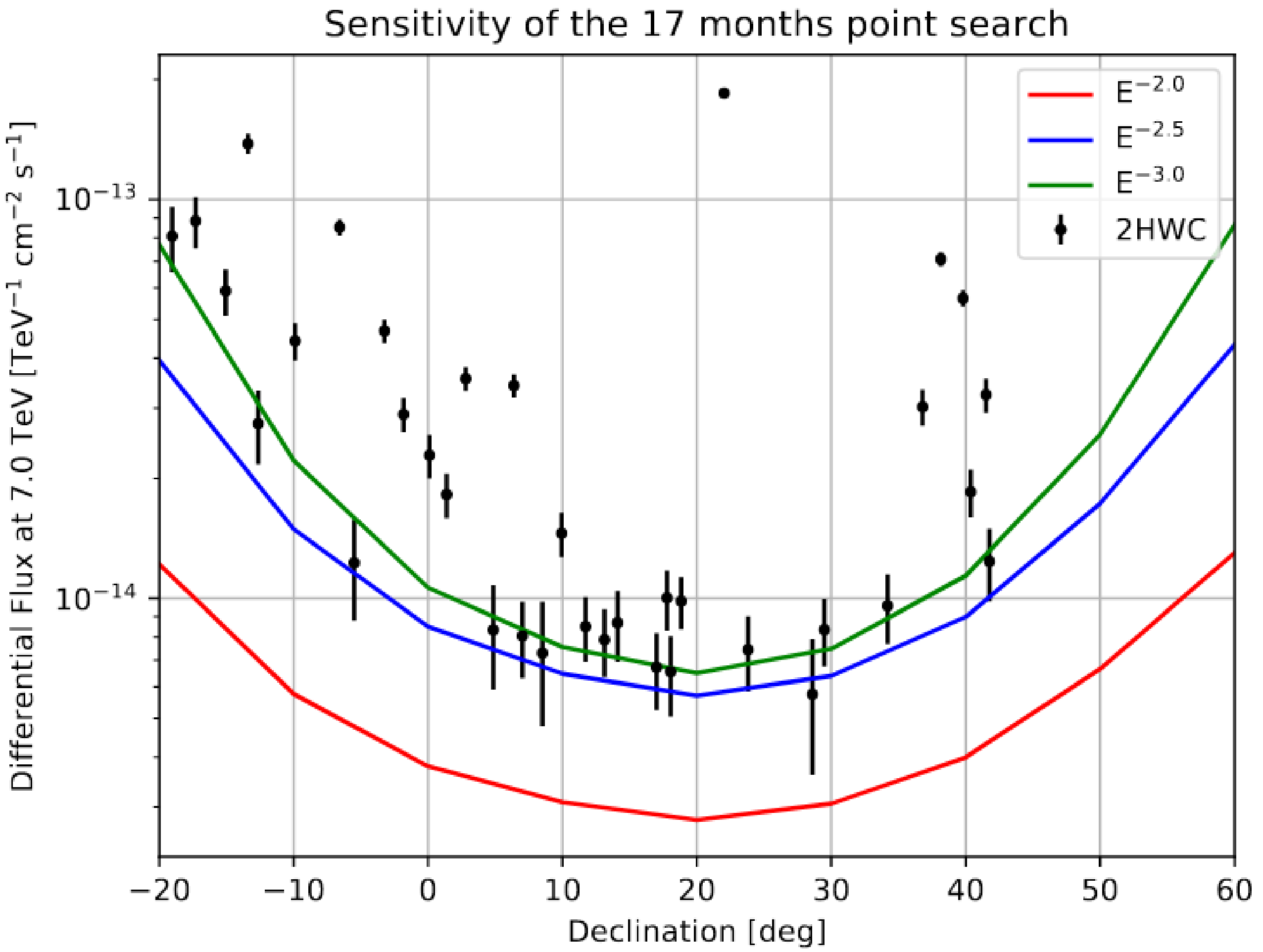
HAWC Detector

- ***22,000 m^2*** *air shower array*
- ***300 Water Cherenkov detectors*** *(WCD)*
- ***200,000 liters*** *of purified water* ***per WCD***
- ***4 sensors (photo-multiplier tubes) per WCD***
- ***Completed March 2015***
- ***Near-continuous duty cycle***
- ***Field of view within 2/3 of sky***
- ***Ideal for all-sky surveys***



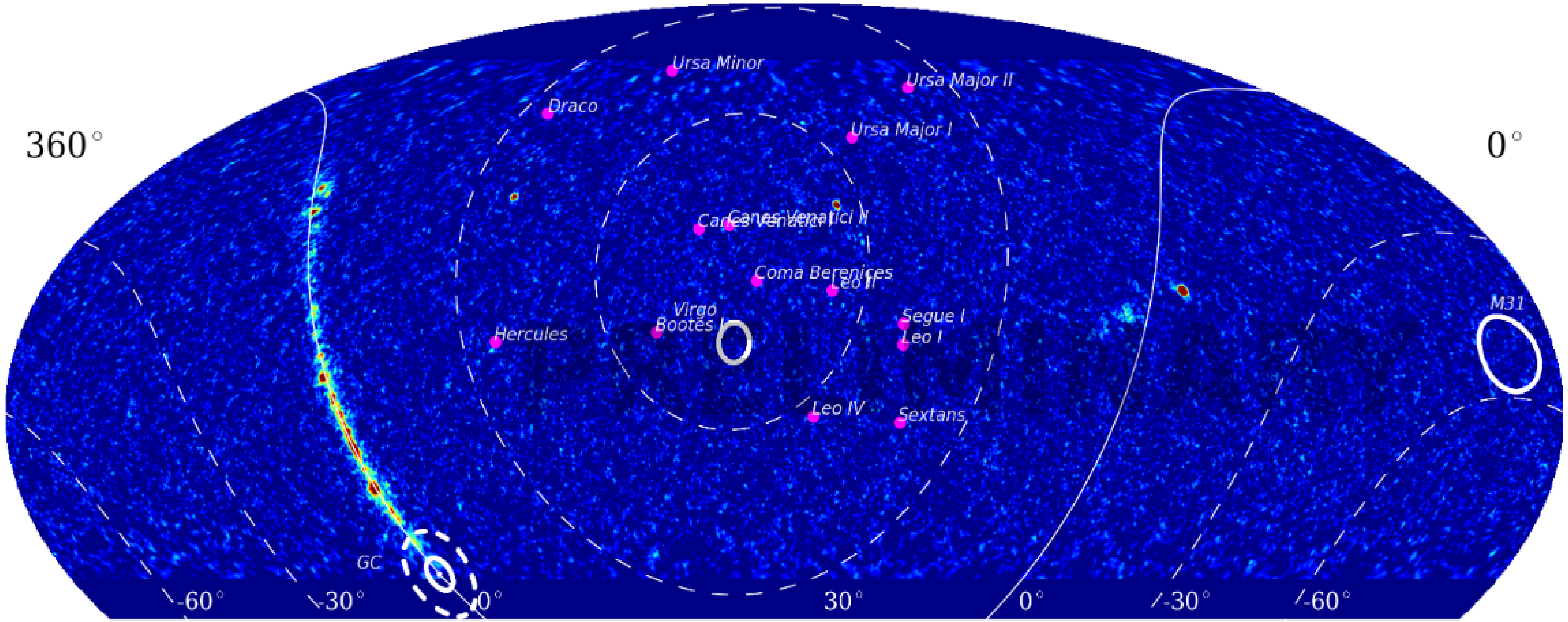
HAWC Properties and Advantages

- Wide simultaneous field of view (~2 sr)
  - Sensitive to highly-extended sources
  - Direct integration for background estimation
- Observation of ~2/3 of sky every day
  - Ability to survey for new sources
  - Can search for DM in multiple regions simultaneously → combined searches
- Archival data
- Sensitivity is declination-dependent
  - Due to atmospheric attenuation of showers
  - Better sensitivity to sources that transit overhead



Abeysekara et. al. *Astrophys.J. 843 (2017) no.1, 40*

Dark Matter Search Targets

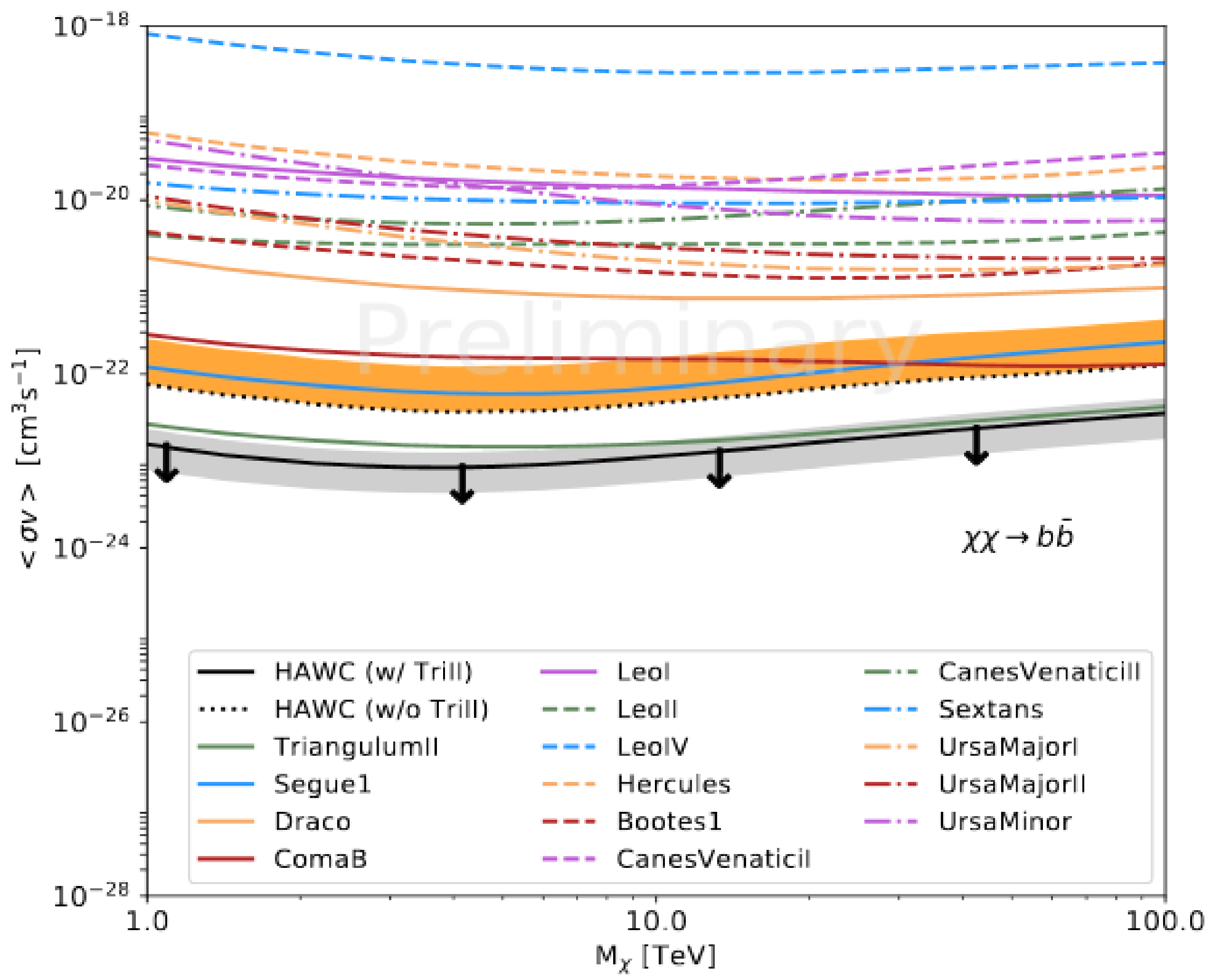


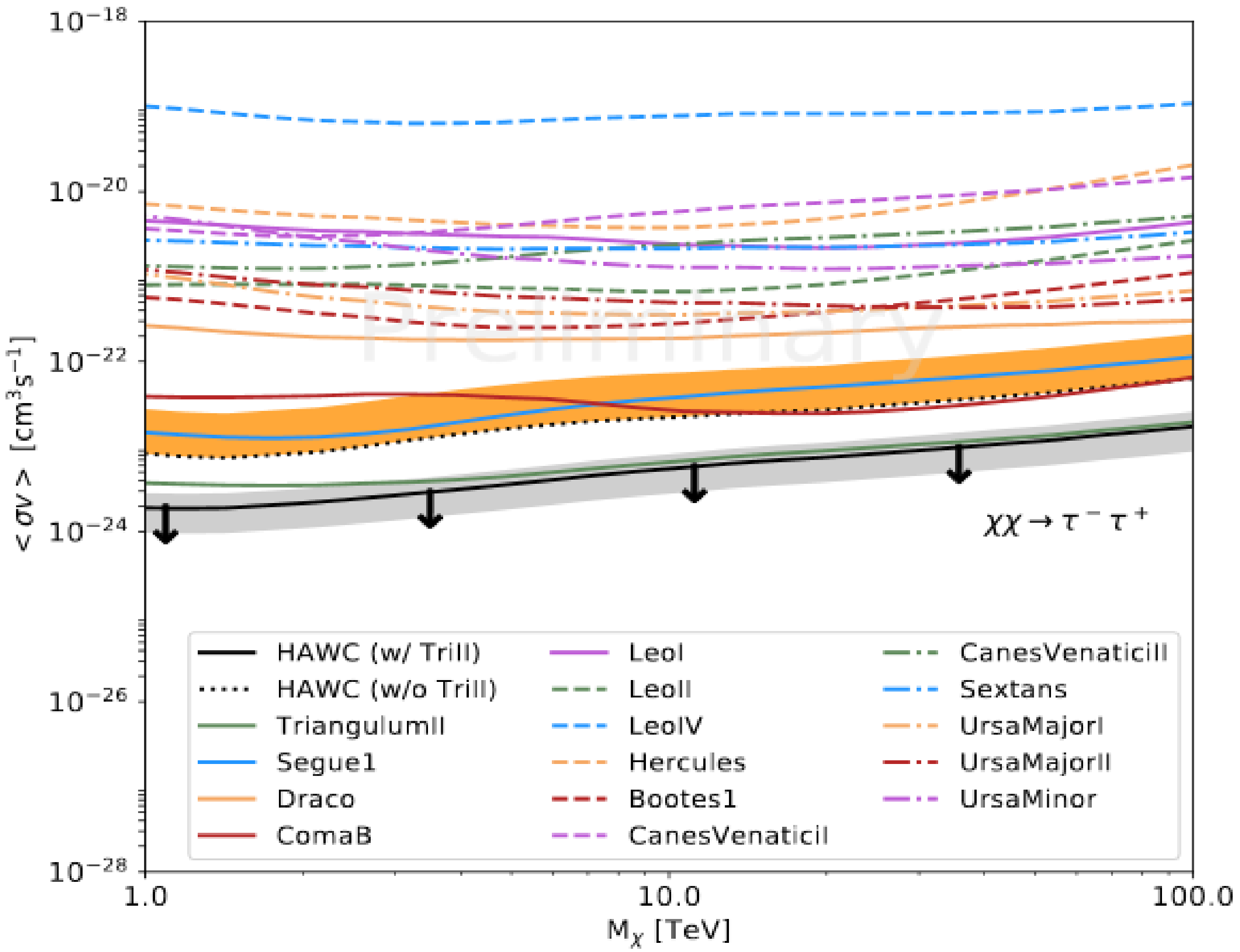
Dwarf Galaxies

- Excellent candidates for DM searches
- Relatively sparse star population
  - No known normal-matter production mechanism for high-energy gamma-rays
  - Very little astrophysical background
- Continuous duty cycle:
  - Can easily perform combined limits
  - Can add additional limits as more are discovered

- Two Classes:
  - Dwarf Spheroidal
    - 15 candidates
    - See next slide
  - Dwarf Irregular
    - 31 candidates
    - See next talk by Sergio Hernandez

Limits from Dwarf Spheroidals





Note: The J-factor of Triangulum II is not well known. Limits are reported with and without Tri II.
See: A. Albert et al., Astrophys. J. 853 (2018) 154.

Joint Limits

- Joint search of the dwarf spheroidals with multiple experiments
  - HAWC, HESS, MAGIC, VERITAS, Fermi-LAT
  - Complete coverage of all multi-GeV through multi-TeV dark matter masses
  - First ever analysis of its kind
- See talk from Monday by Louise Oakes and proceedings

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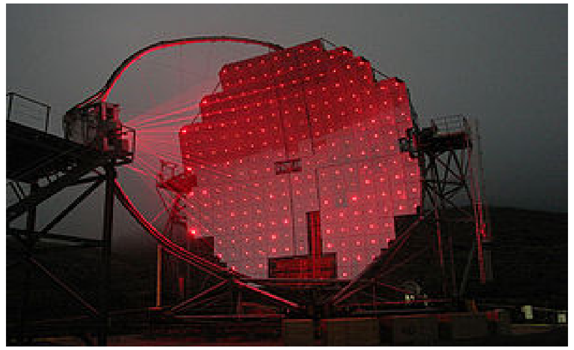

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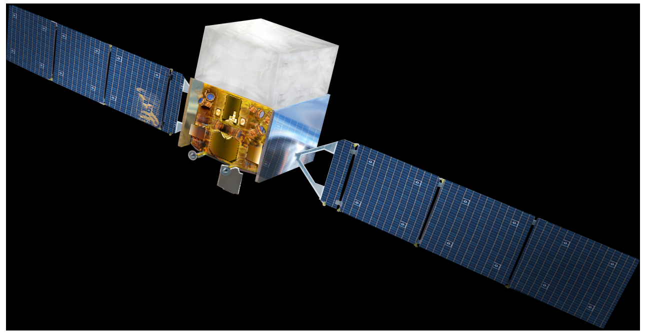


Extended Targets

- M31 galaxy, Virgo Cluster, Galactic halo
- Wide field of view needed
- Allows for full treatment of morphology
- Background estimation
  - Need “off” regions sufficiently far from source to avoid signal contamination
  - Wide field of view and continuous duty-cycle allows for simultaneous observation of “on” and “off” regions
- Need to consider systematics from spatial profile
- Particularly well-suited for setting decay lower-limits

Density Profile Uncertainty

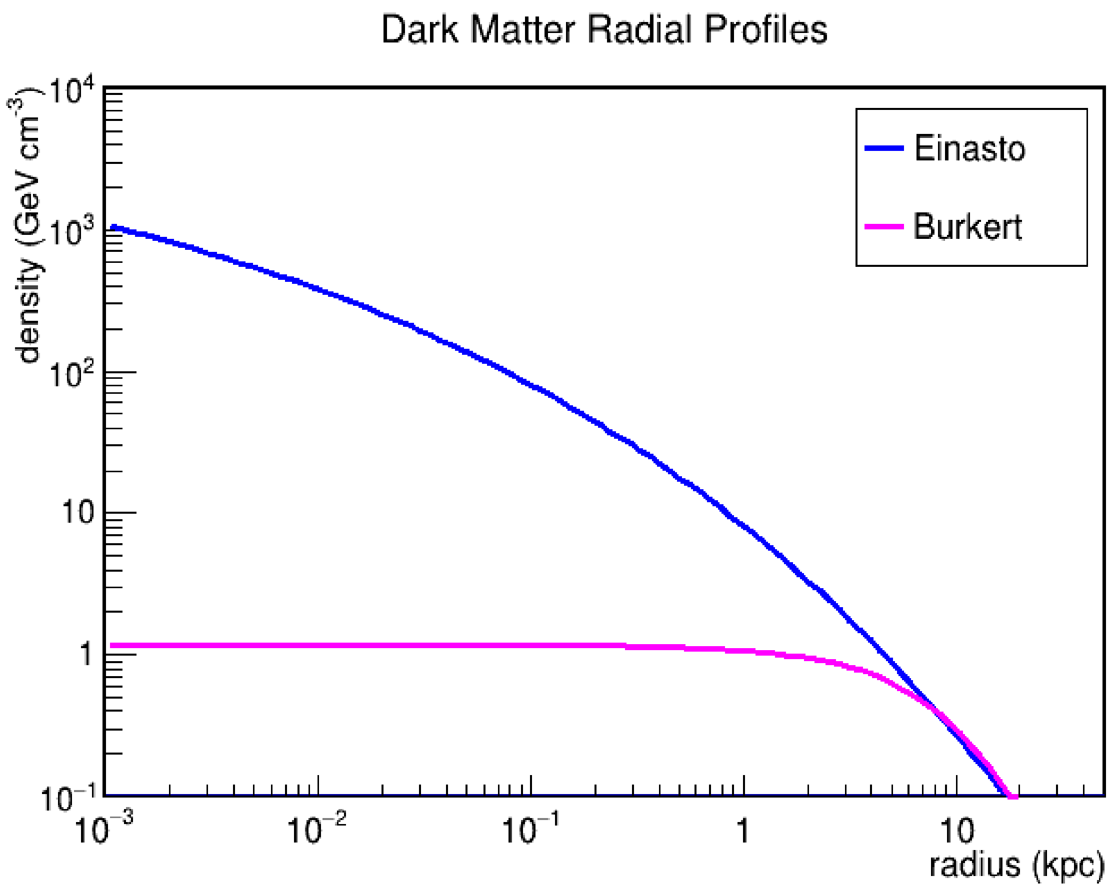
- Behavior of dark matter density not well constrained towards center of large halos
- J-factors and D-factors typically have large systematic from density profile
- Signal boosts from theorized substructure contribution

Einasto Profile (Cuspy)

$$\rho(r) = \rho_s e^{\frac{-2}{\alpha}[(r/r_s)^{\alpha}-1]}$$

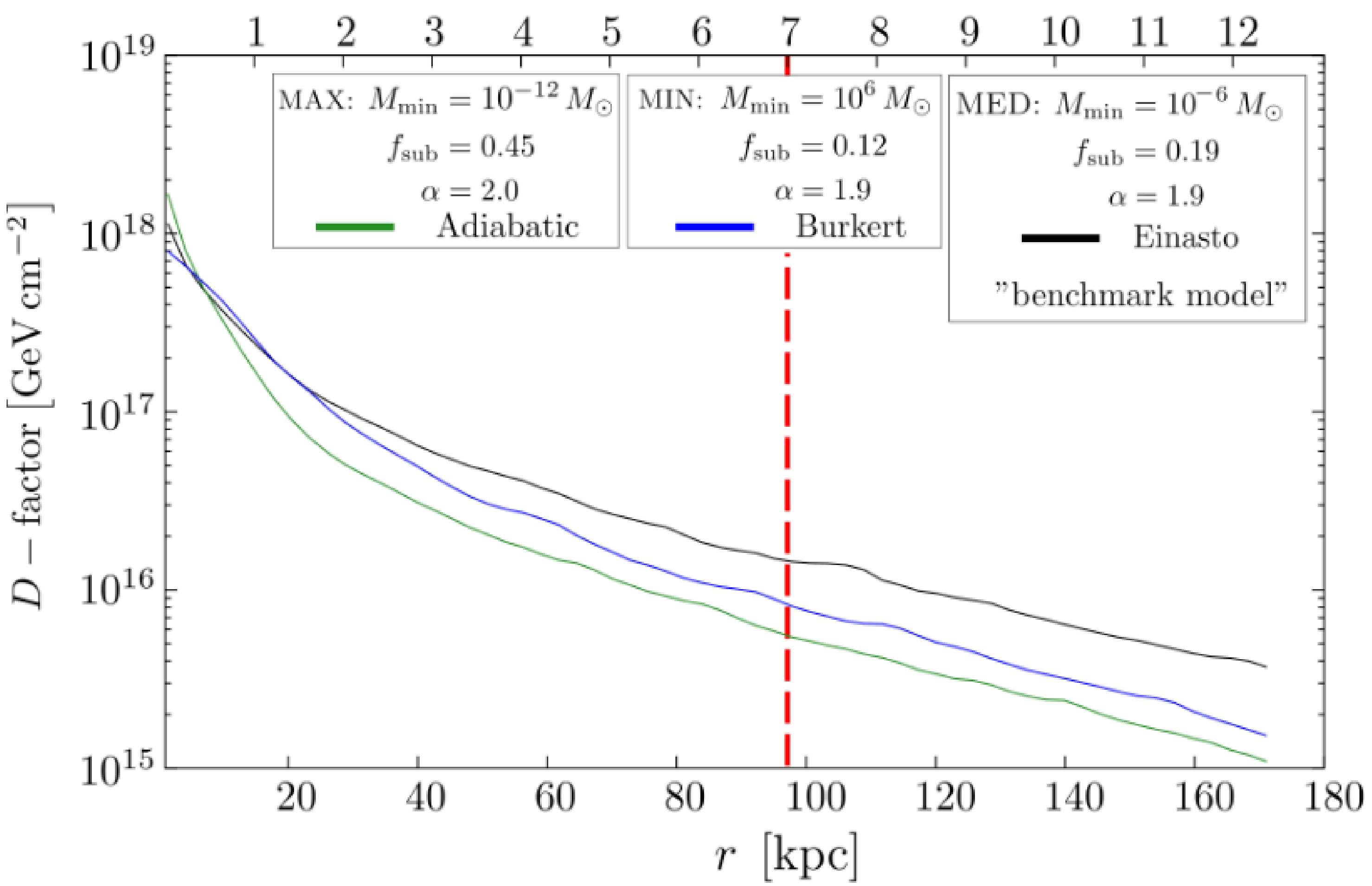
Burkert Profile (Cored)

$$\rho(r) = \frac{\rho_s}{(1+r/r_s)(1+(r/r_s)^2)}$$



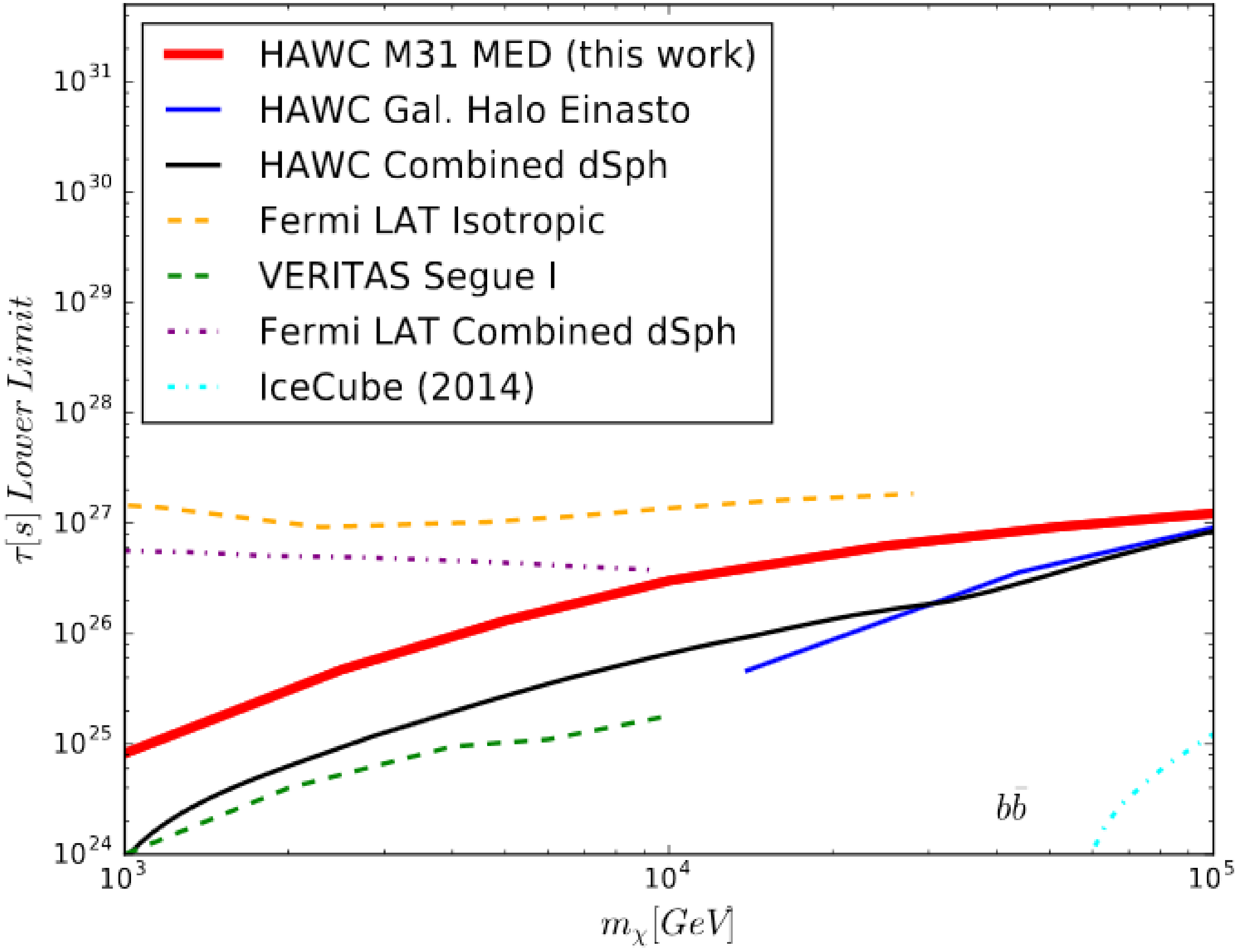
M31

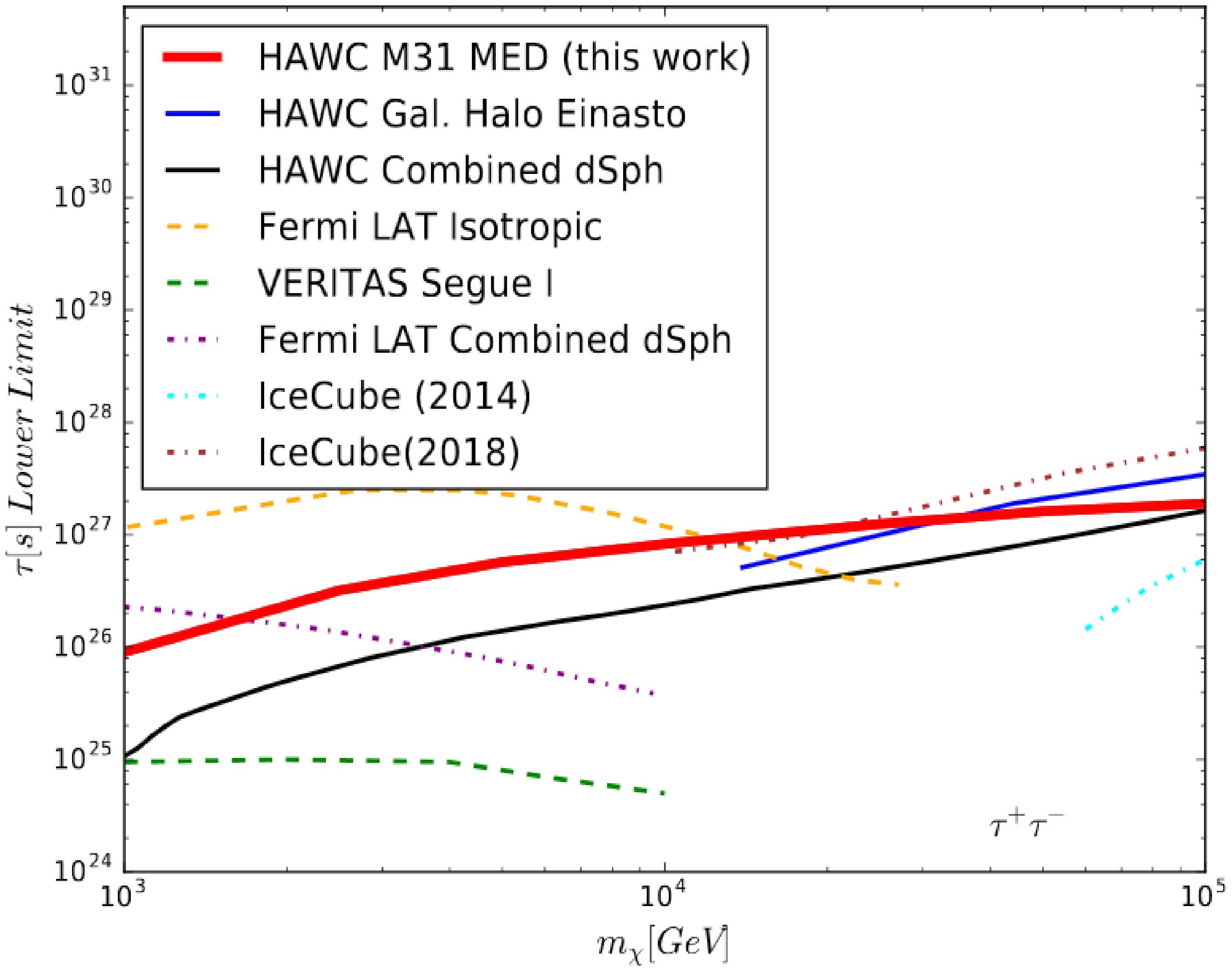
- Closest galaxy (besides the Milky Way)
  - Combined with high dark matter content, gives large expected flux
- Also highly extended
  - Requires treatment of morphology
  - Considered different density profiles
- Substructure
  - Different models of substructure content considered
  - Results shown for median model
- Yields strong decay limits



See: Albert et. al. *Search for Dark Matter Gamma-ray Emission from the Andromeda Galaxy with the High-Altitude Water Cherenkov Observatory*

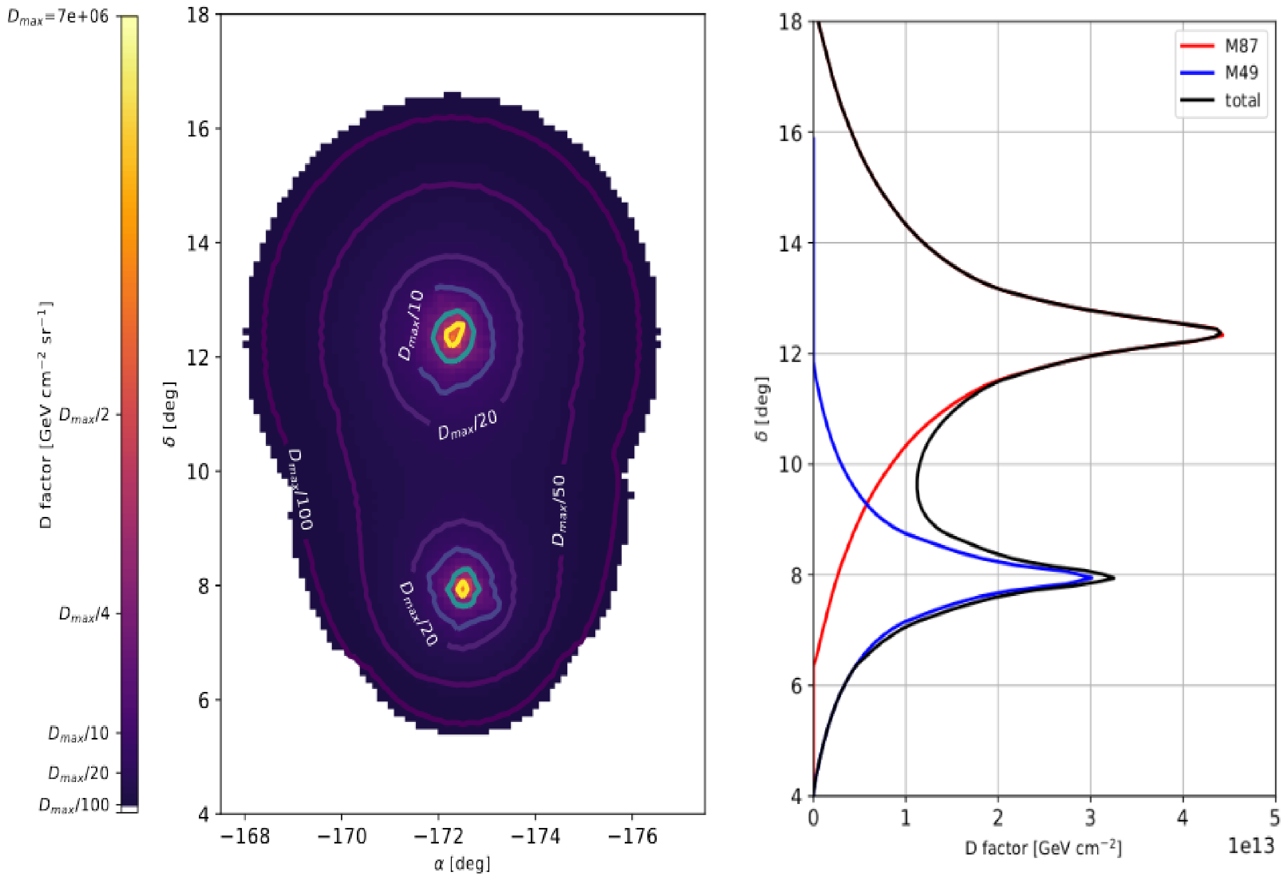
Decay Limits from M31



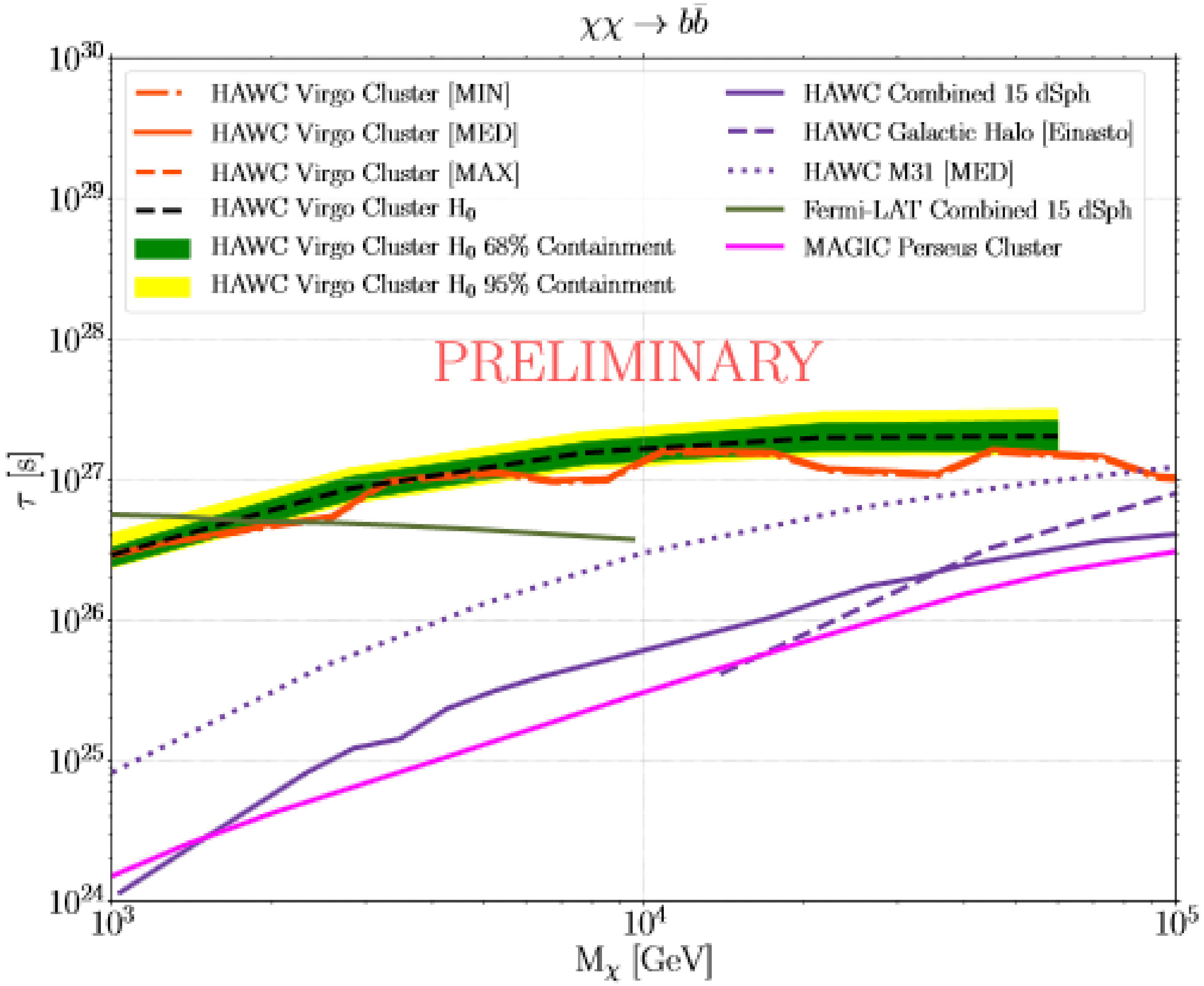


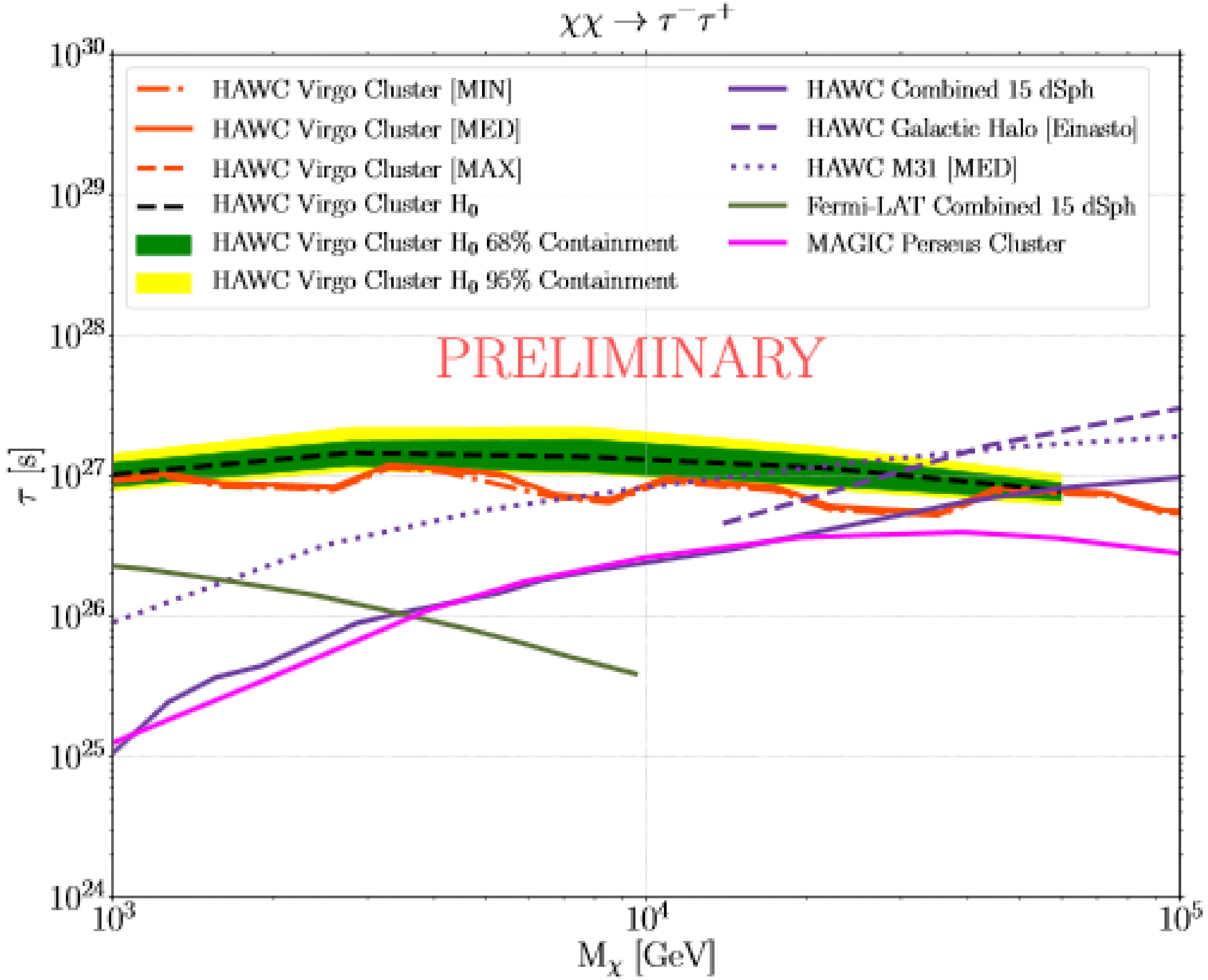
The Virgo Cluster

- Highly extended
  - ~10 x10 degrees
  - Morphology consists of two distinct peaks
- Different models of substructure contribution
  - High, median, and low substructure content models
  - Only results from median case shown here
- High dark matter content
- Nicely compliments constraints from other experiments
- See poster presentation by Tolga Yapici for details



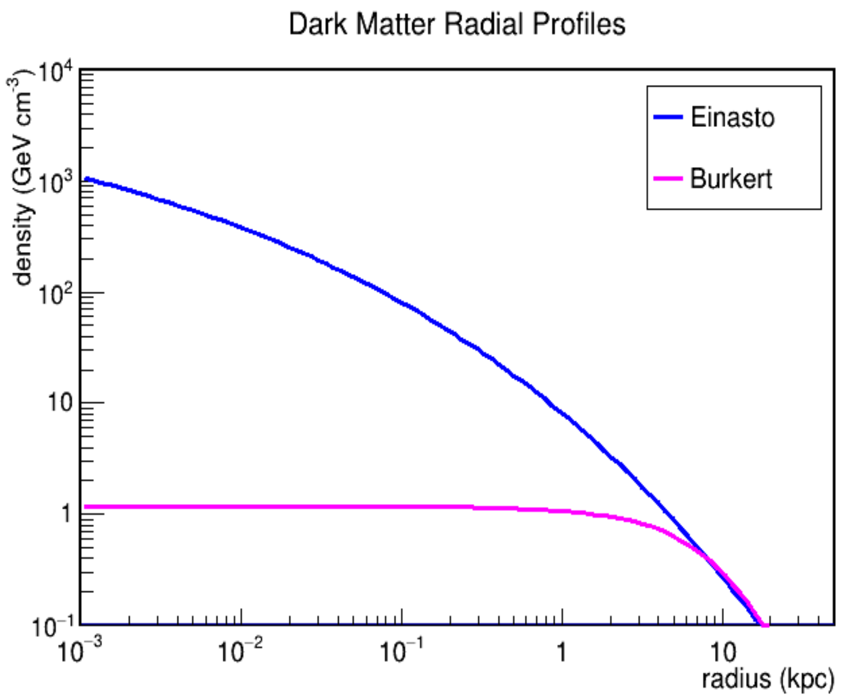
Decay Limits from Virgo





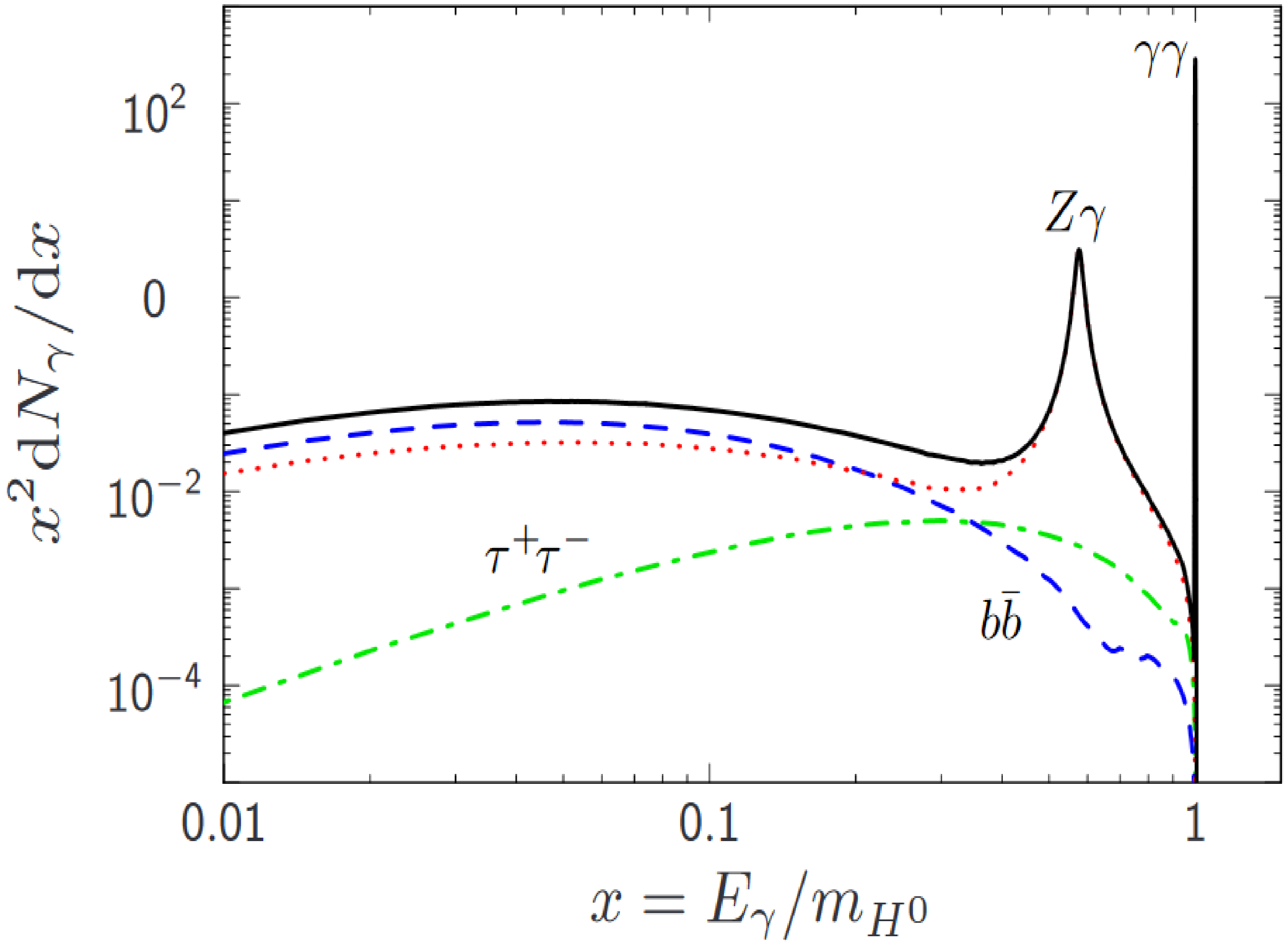
The Galactic Halo

- Closest large halo → large expected flux
- Largest flux expected towards the Galactic center, however:
  - Large systematic from unconstrained density profile
  - Possible contamination from visible-matter sources
- HAWC field of view enables observation of larger regions further from the center
  - Mitigates effect of density profile
  - Avoids contamination from sources in Galactic plane
- Previous analysis in Fermi Bubble region (see: HAWC Collaboration, A. U. Abeysekara et al., JCAP 1802 (2018) 049.)
- Current analysis using even wider region (see poster and proceedings by Joe Lundeen)



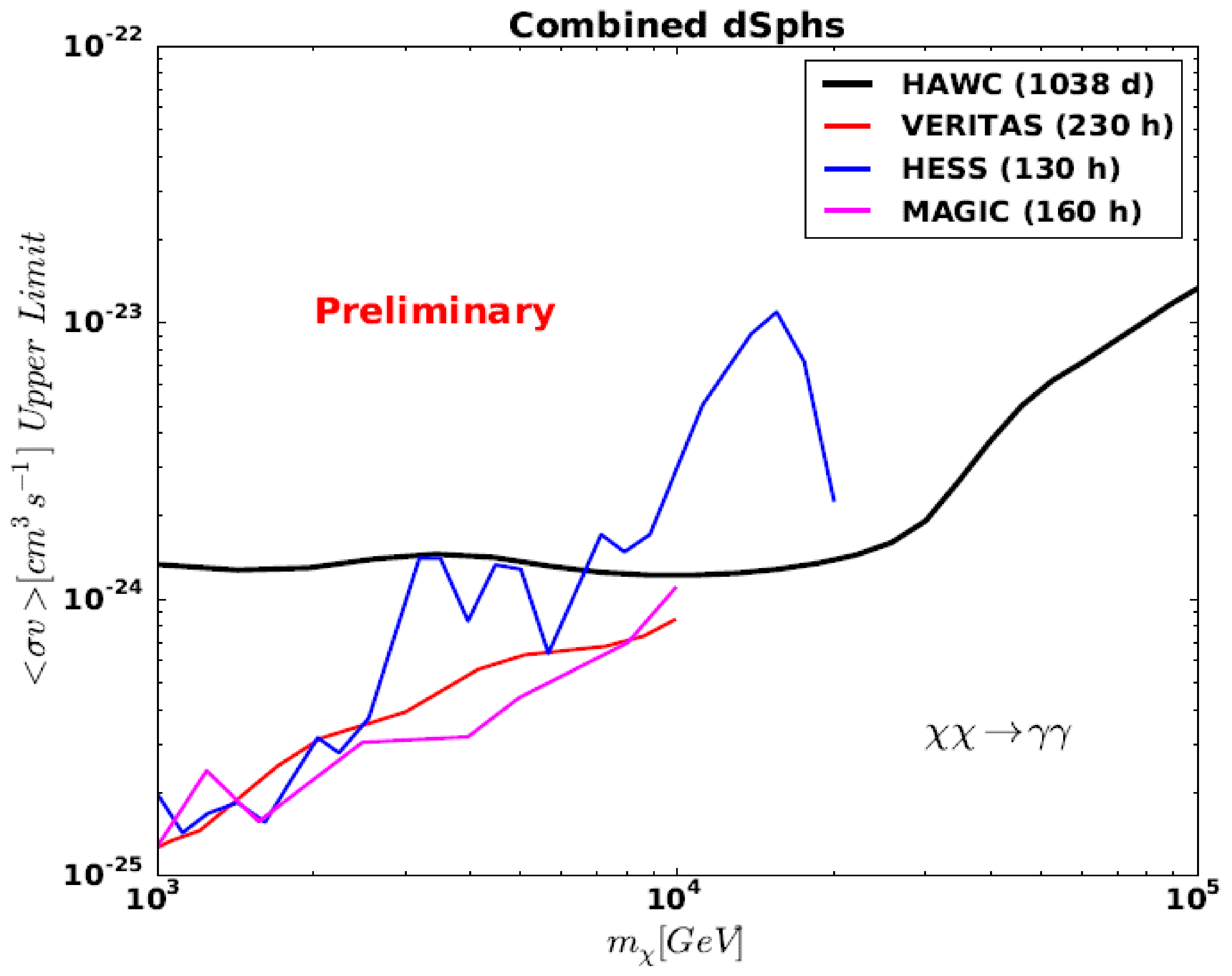
Gamma-ray Lines

- Direct annihilation of dark matter to gamma-rays
- Manifests as a delta function in energy spectrum
- "Smoking gun" for dark matter
  - Only mechanism that can produce this shape at TeV scale
  - Location of line immediately reveals the dark matter mass.
- New energy estimation techniques allow HAWC to search for this feature



First Limits on Gamma-ray Lines

- Performed combined upper limit using dwarf spheroidal galaxies
- Most constraining limits above ~20 TeV
- Nicely compliment searches by IACTs



Summary

- HAWC's wide field of view and continuous duty cycle make it ideal for surveys and extended source analysis
- Can easily perform combined searches
  - Improves sensitivity of constraints
  - Currently extending to combinations with other experiments
- Sensitive to extended sources: yield strong decay limits
- Now able to search for gamma-ray lines
  - Energy estimators also allow searches at higher masses
- More results coming from Galactic halo

Backup Slides

Likelihood Fitting

- Use log likelihood ratio used to identify signals
  - N=observed counts in each bin
  - B=expected background
  - S=expected excess counts from dark matter spectru
  - Treat counts in each bin as Poisson-distributed
  - Calculate likelihoods for both null (background) hypothesis and dark matter hypothesis
- Wilks' theorem
  - TS is chi-squared distributed
  - Allows us to treat σ as significance for 1 degree of freedom
- 95% confidence level
  - Fit such that TS=TSmax-2.71

$$L_0 = \frac{e^{-B} B^N}{N!}$$

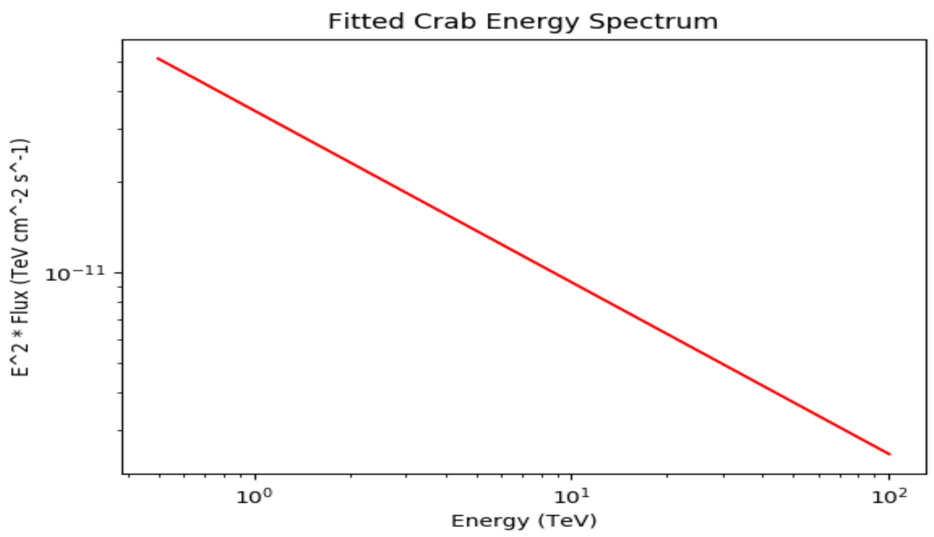
$$L = \frac{e^{-(B+S)}(B+S)^N}{N!}$$

$$TS = -2 ln\left(\frac{L_0}{L}\right)$$

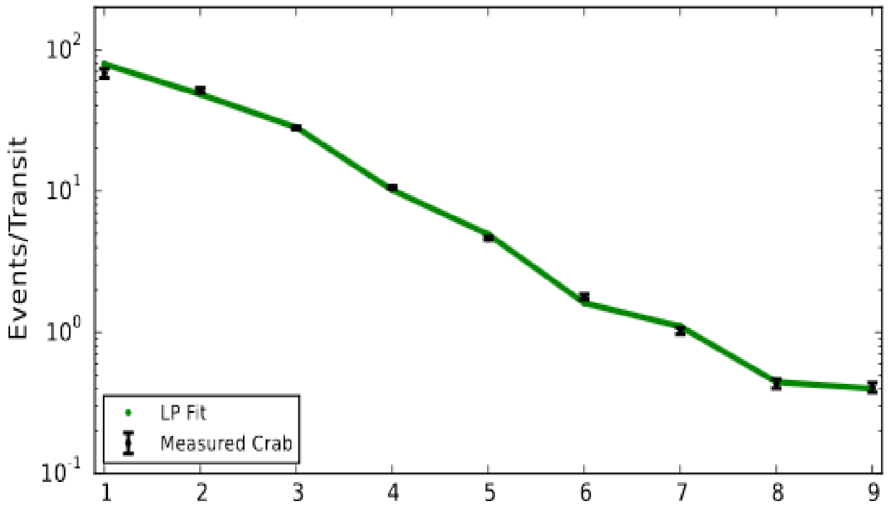
$$\sigma = sign(\phi)\sqrt{TS}$$

Forward Folding

- Due to energy resolution, HAWC does not bin events by energy
- Binned by fraction of PMTs triggered (fhit)
- fhit spectrum converted back to energy spectrum
  - Use simulation of detector response to energy spectra
  - Map observed nhit spectrum back to E-spectrum that best reproduces it in simulation
  - Use maximum likelihood



Forward folding



Direct Integration

- Majority of HAWC events are charged cosmic rays
  - Roughly isotropic across the sky
  - Some are removed through quality cuts, but still dominate post-cut data
- Background estimated through direct integration
  - Average event rate within 2 hours (30 degrees) of a source
  - Events are background-dominated → average rate is approximately background rate
- R.Atkins, et al. Astrophys.J. 595 (2003) 803-811
- See also: D. Fiorino, Thesis.

Density Profile Uncertainty

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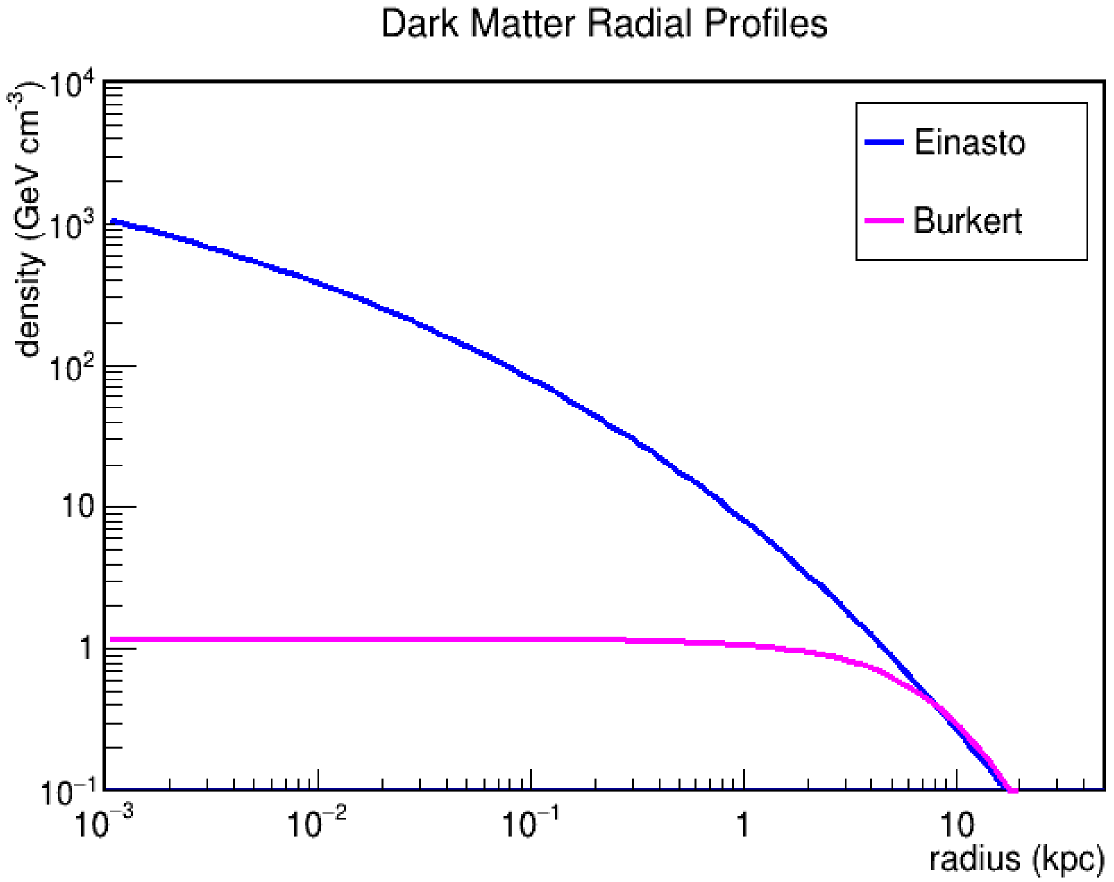

The Galactic Halo

- Closest large halo → high expected dark matter signal
- HAWC can observe highly extended region of the halo
- Requires very careful treatment of background
  - Extends across entire sky
  - If dark matter does produce gamma rays, all sky regions will contain some contribution from Galactic halo
  - No true “Off” region for background estimation
  - Need to take into account signal contamination in background
- Highly sensitive to density profile

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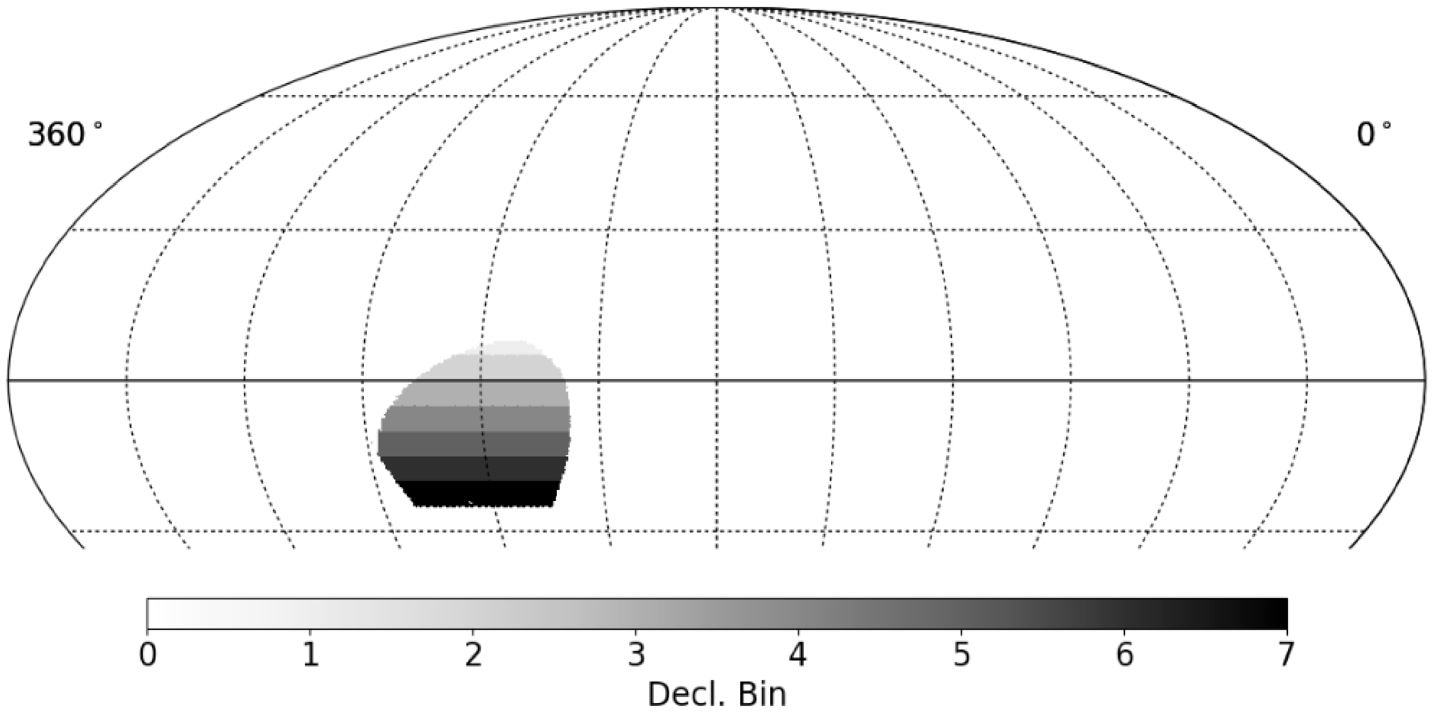
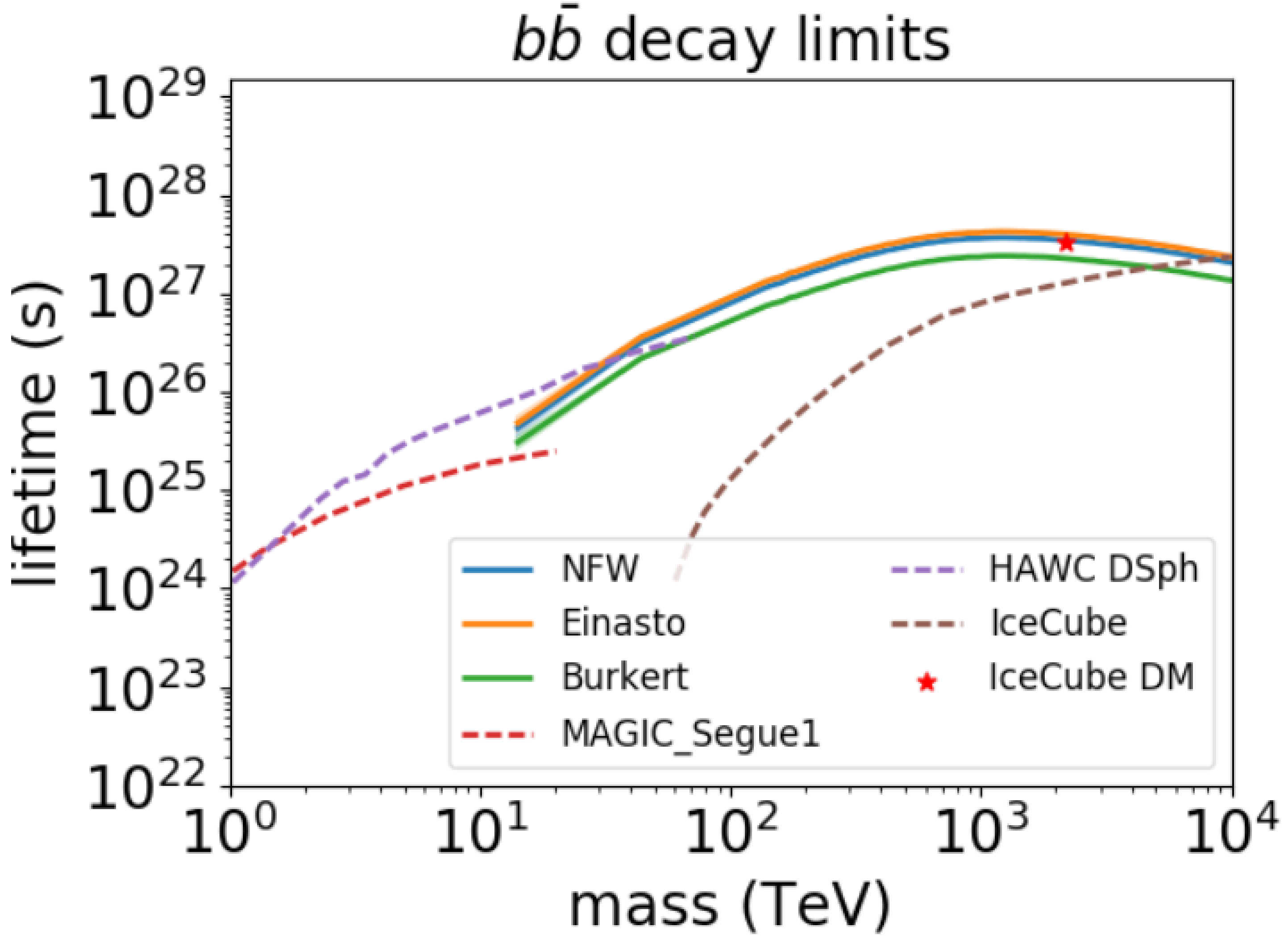
Decay Limits from the Galactic Halo



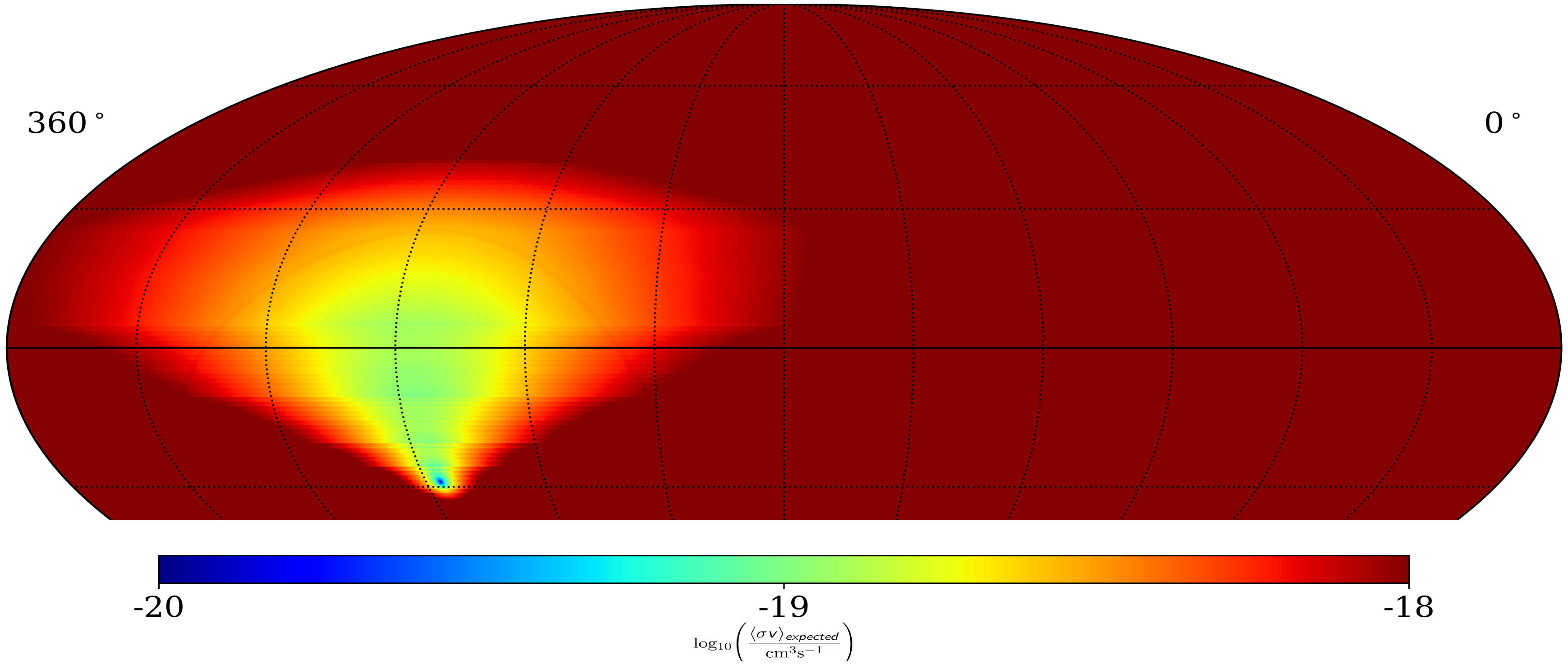


Obtained these limits using just a fairly small part of the halo.

Limits will improve with the more rigorous search (see poster by Joe Lundeen)

Galactic Halo Sensitivity

- Obtained by combining estimates of dark matter sensitivity with modeled density profile
- Map of point source “expected limits”: show which pixels are expected to be most constraining
  - Most sensitive pixels are combined into full ROI
  - Remaining sky is used as “off” region of background estimation



Galactic center is at edge of HAWC field of view
Limits are mostly driven by points overhead